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The impact of climatic and atmospheric teleconnections on the brine inventory over the Laptev Sea shelf between 2007 and 2011

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Key Points:
- Summer brine inventory varies interannually by up to 50% over the Laptev Sea shelf
- Winter atmospheric teleconnections are probably the main factor controlling brine inventory
- We hypothesize that summer brine inventory is modulated by brine export

Supporting Information:
- Supporting Information S1
- Supporting Information S2

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Abstract Export of brine-enriched water from Siberian shelves is thought to be a key parameter in maintaining the Arctic Halocline, which isolates the fresh and cold surface water from the warm Atlantic water and thus prevent dramatic change in the Arctic sea-ice thermodynamic. In this study, we used 5 years of oxygen isotope and hydrological summer surveys to better understand the factors controlling the brine inventory and distribution over the Laptev Sea shelf. The inventory was maximal in 2011 and 2007 and minimal in 2010. The brine inventory interannual variations are coherent with the winter Arctic Oscillation index that was maximal in 2011 and 2007 and minimal in 2010, which is known to modulate Arctic winds and sea-ice export pattern. While we should remain cautious since our record is limited to 5 years, our results suggest that the combined effect of the Arctic Oscillation and of the Arctic Dipole is the main factor controlling the annual variations in the inventory of brine-enriched waters from the Laptev Sea shelf between 2007 and 2011, especially during extreme negative Arctic Oscillation and Arctic Dipole conditions as in 2010.

1. Introduction

Loss of thick, multiyear ice has been observed in the Arctic Ocean since the late 1960s [*Derksen et al.*, 2012]. This thick ice is replaced by thin, first-year ice that is more sensitive to atmospheric and oceanic forcing [*Ballinger and Rogers*, 2014]. While a lot of attention went to estimate the sea-ice extent itself and its export from the Arctic Ocean [*Langehaug et al.*, 2013], less information is available on the shelf processes that influence the pan-Arctic sea-ice budget indirectly as the brine rejection resulting from sea-ice formation and its role on maintaining the Arctic halocline.

When water starts to freeze, salt is rejected from the newly formed ice and increases the salinity of the underlying water, creating brine-enriched water. The brine rejection has a profound impact on the local and regional oceanography because of the brine-related convective and advective patterns [*Bauch et al.*, 2012]. Brine-enriched water formed within the Siberian shelves, and notably over the Laptev Sea shelf, is exported to the Arctic halocline [*Bauch et al.*, 2009b]. The Arctic halocline is an admixture of river and brine-enriched water, which makes it denser than the fresh surface water layer but still fresher and colder than the Atlantic-derived water underneath [*Aagaard et al.*, 1981]. The halocline insulates the surface layer from the warmer underlying water shielding the sea-ice cover from an upward heat flux and preventing the enhancement of the Arctic Ocean sea-ice decline. While the role of brine-enriched waters in maintaining the Arctic halocline is well documented [*Bauch et al.*, 2011b], the hydrographic and atmospheric processes potentially controlling the export rate from the shelves are still unclear, especially in the scope of a warmer Arctic. We need to resolve which factors are controlling the inventory of brine-enriched waters from Arctic shelves to the halocline and how those factors will be affected by ongoing and projected climatic and oceanographic changes in the Arctic.

It has been suggested that climatic and atmospheric teleconnection, as the Arctic Oscillation (AO) and the Arctic Dipole (AD), are major factors influencing, notably, sea-ice export [*Watanabe et al.*, 2006; *Wu et al.*, 2006; *Wang et al.*, 2009], sea-ice extent [*Overland et al.*, 2012; *Ballinger and Rogers*, 2014], and freshwater inventory [*Morison et al.*, 2012; *Thibodeau et al.*, 2014]. On the other hand no link between ice export from the Laptev Sea region and AO was found for the 1992–2011 time period [*Krumpen et al.*, 2013]. It is thus important to investigate the role of those major teleconnections on the sea-ice-related brine inventory in

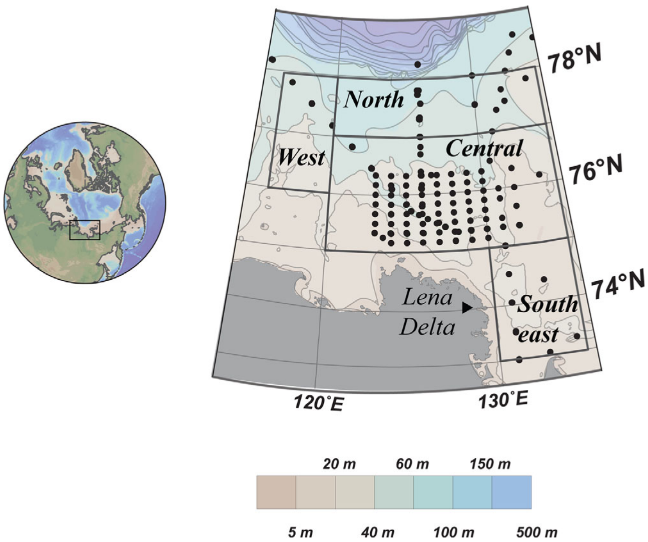

Figure 1. Map of the Laptev Sea shelf with sampling stations location (black dots). Rectangles represent the interpolation zones used to calculate the brine inventory.

order to better understand how it is related to sea-ice formation and/or to the transport (export) of brine after their rejection from the newly formed sea-ice.

Here we present more than 1800 salinity and oxygen isotope (δ^{18}O) measurements that were used to estimate the brine inventory over the Laptev Sea shelf from 2007 to 2011. We compared the estimate of brine inventory to climatic and atmospheric teleconnection indexes in order to better understand the role of large-scale atmospheric regimes on brine inventory.

2. Methods

Samples were collected during TRANSDRIFT expeditions in Arctic summer 2007 (29 August to 17 September), 2008 (7 August to 25 September), 2009 (9 September to 16 September), 2010 (9 September to 20 September), and 2011 (25 August to 4 September) (Figure 1). Water samples were taken with a Conductivity-Temperature-Depth (CTD)-rosette. Individual temperature and conductivity measurements were obtained using Sea-Bird SBE-19+ with accuracy ± 0.005°C and ± 0.002 S/m in conductivity. In addition to CTD measurements, bottle salinity was determined directly from the same water samples taken for δ^{18}O analysis using an *AutoSal 8400A salinometer* (Fa. Guildline) with a precision of ± 0.003 and an accuracy of at least ± 0.005. Oxygen isotopes were analyzed at the Leibniz Laboratory (Kiel, Germany) except the 2010 samples, which were analyzed at the Stable Isotope Laboratory (Oregon State University, United States). All isotope measurements were performed using the classical CO_2-water equilibration method [*Epstein and Mayeda*, 1953]. The overall measurement precision for all δ^{18}O analysis was $\pm 0.04‰$ or better. The ^{18}O/^{16}O ratio is given in respect to V-SMOW in the δ-notation [*Craig*, 1961].

The brine contribution due to sea-ice formation can be quantified by applying a mass-balance calculation based on three end-members [*Bauch et al.*, 1995]. It is assumed that each sample is a mixture between marine water (f_{mar}), river runoff (f_{riv}), and sea-ice meltwater (f_{sim}). From this, we can assume the following equations:

$$f_{mar} + f_{riv} + f_{sim} = 1$$

$$f_{mar} * S_{mar} + f_{riv} * S_{riv} + f_{sim} * S_{sim} = S_{measured}$$

$$f_{mar} * O_{mar} + f_{riv} * O_{riv} + f_{sim} * O_{sim} = O_{measured}$$

where f_{mar}, f_{riv}, and f_{sim} are the fraction of each end-member in a water parcel and S_{mar}, S_{riv}, S_{sim}, O_{mar}, O_{riv}, and O_{sim} are the corresponding salinities and δ^{18}O values of the end-members; $S_{measured}$ and $O_{measured}$ are the salinities and δ^{18}O values of the water samples [*Bauch et al.*, 2005]. Respective end-members S and O values (Table 1) were chosen accordingly to past Laptev Sea investigation [*Bauch et al.*, 2009a, 2010, 2011a, 2011c].

Sea-ice meltwater fractions may be negative when sea-ice forms and freshwater is extracted as sea-ice from the water column and the sea-ice-related brine remains within the water column. Negative fractions of sea-ice meltwater are referred as sea-ice-related brine contribution and will for simplicity also be referred to as "brine." Brine inventories were calculated by integrating the fractions of brine over the whole water column, which yields the averaged thickness of the water

Table 1. End-Member Values for Mass-Balance Calculations

End-Member	Salinity	δ^{18}O
Marine	34.92	0.3
River	0	−20
Sea ice	4	Surface +2.6

Table 2. Brine Inventory for the Different Zones of the Laptev Sea (km^3)[a]

Years	Central 74–76°N 120–135°E 94,960 km^2	South-East 72–74°N 130–136°E 43,133 km^2	North 76–77°N 120–135°E 42,824 km^2	West 75–77°N 114–120°E 17,7784 km^2	Total
2007	267	72	109	58	506
2008	229	61	56	63	409
2009	199	81	42	10	332
2010	124	71	54	15	265
2011	284	62	160	47	554

[a]Latitude, longitude, and surface area of the different zones are indicated.

column that has been extracted and exported as sea-ice. The inventory was calculated using the averaged thickness of brine extrapolated over the surface using the weighed-average tool in Ocean Data View. We divided the Laptev Sea shelf into four parts in order to track the brine inventory distribution annually (Figure 1 and Table 2).

3. Results

The brine inventory over the whole Laptev Sea shelf was maximal in 2007, 2011, and minimal in 2010 (Table 2), this was mostly due to variation within the central part of the shelf (Figure 2). However, an important increase in brine was also observed over the northern part of the shelf in 2007 and 2011. Minimal amount of brine was found over the western part of the shelf in 2009 and 2010. The distribution was similar in 2007 and 2011 and mostly located over the central and northern part. Brine was restricted mostly to the central zone in 2008, 2009, and 2010. We observed that water with high brine content ($>$7%) occupied most of the water column (0–35 m) over the whole 126°E transect with a maximum at intermediate depth (20 m) between 75.5°N and 76°N in 2011 (Figure 3). In 2007, water with high-brine content occupied the whole water column in the southern part of the transect and reached 76.5°N within the surface layer ($<$10 m) while in 2008 the high brine content spread northward at intermediate and bottom depth but not at the surface. In 2010, the only zone of high-brine content was located at the bottom, within the southern part of the transect.

4. Discussion

4.1. Interannual Variation in Brine Distribution and Inventory

The interannual variation in brine distribution and inventory may be caused by either variation in the volume of brine produced or postformation transport (import and export). The volume of brine rejection depends on the total sea-ice production, which is primarily controlled by the polynya activity, a zone of open-water formed by offshore winds pushing the pack ice away from the fast-ice [*Smith et al*., 1990]. Despite indications than polynya-related sea-ice production might not be sufficient to explain historical summer-to-winter salinity changes, it was shown that total sea-ice production varied coherently with polynya activity within the Laptev Sea [*Dmitrenko et al*., 2009]. Thus, if the brine inventory is modulated by sea-ice production, we expect the trend of polynya-related sea-ice production to be recorded within our brine inventory. Daily sea-ice production rate within polynya can be estimated via remote sensing [*Willmes et al*., 2011]. However, no similarity was observed between our brine inventory and remote sensing-derived sea-ice production from the Laptev Sea polynya between years 2007–2011 (Figure 4) [*Preusser et al*., 2014]. Thus, the available data, as of today, suggest that interannual variations in brine inventory between 2007 and 2011 are not due to change in the amount of brine rejected by sea-ice formation within the Laptev Sea shelf but rather to postformation transport. Difference in the exact timing of the sampling is relatively small (about 10 days) and even if we consider that export of brine can occur during summer, it appears unrealistic that this would account for the large variation (50%) between the lowest and highest brine content years given an average mean residence time of 3.5 $\pm$ 2 years of Siberian shelf waters [*Schlosser et al*., 1994]. Moreover, we observed no systematic trend between the early and late sampling during the same year.

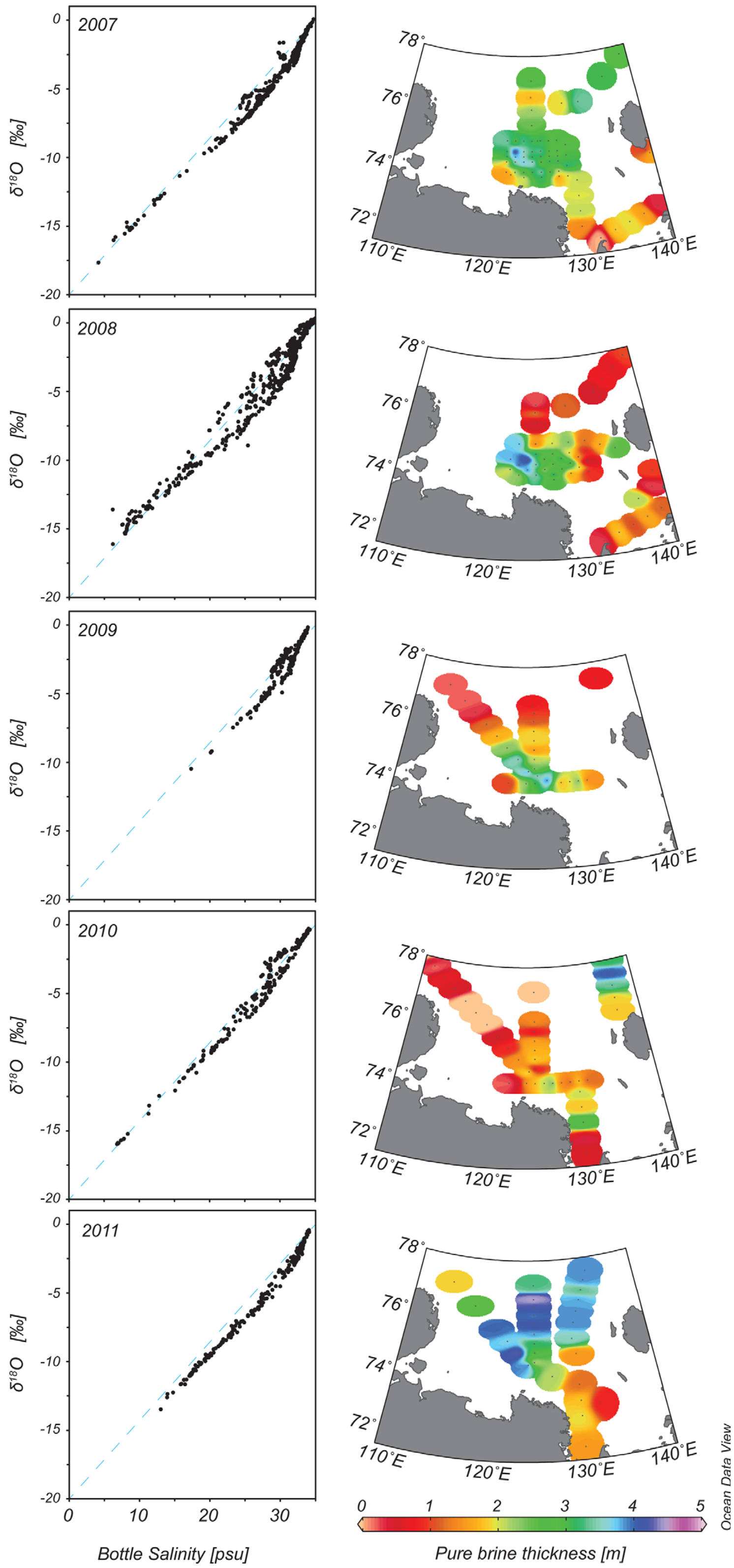

Figure 2. On the left, we plotted water $\delta^{18}O$ against salinity for each sampling year (blue-dashed line represents the mixing line between river and Atlantic-derived end-members). On the right plot, we plotted the sea-ice-related brine inventory (thickness of extracted freshwater in meters) over the Laptev Sea shelf for years 2007–2011. Note that brine inventory is calculated from the negative fractions of sea-ice meltwater calculated from the water mass analysis (for further explanation see text).

4.2. Climatic and Atmospheric Teleconnections

Regional and local oceanography will control the transport of brine-enriched water, which will be influenced by externally (such as wind or ice motion) driven currents. It has been suggested that wind forcing is the main driver for summer oceanography within the Laptev Sea [*Dmitrenko et al.*, 2005; *Bauch et al.*, 2009b] and more recently that climatic and atmospheric teleconnection could strongly influence the river water inventory [*Thibodeau et al.*, 2014]. While this link is probably less pronounced in winter due to the sea-ice cover [*Dmitrenko et al.*, 2005, 2009], wind-driven under-ice circulation and saline intrusion were recently highlighted during winter in the Laptev Sea [*Dmitrenko et al.*, 2010; *Janout et al.*, 2013] and thus investigating potential link between climatic and atmospheric teleconnection and the Laptev Sea shelf brine inventory is important. Interestingly, we observe a strong similarity between the brine inventory and AO, AD, and NAO (North Atlantic Oscillation) winter indexes for year 2007–2011 (Figure 4) but no similarity with the summer indexes, which is contrasting with the summer freshwater inventory [*Thibodeau et al.*, 2014]. This highlights the fact that the mechanisms controlling the summer brine inventory are active during winter. Two hypothesizes can be drawn to explain this link: (1) teleconnections influence the sea-ice production [*Dmitrenko et al.*, 2009], which should be reflected within the summer brine inventory or (2) teleconnections create a significant export of brine between their formation and summer time. However, as highlighted above, we observed no similarity between the remote sensing-derived sea-ice production and our brine inventory, which prevent us to pursuit this hypothesis. While the influence of teleconnection on freshwater and sea-ice export is well documented in the Arctic [*Steele et al.*, 2004; *Watanabe et al.*, 2006; *Wu et al.*, 2006; *Wang et al.*, 2009; *Morison et al.*, 2012], a link between the inventory of brine-enriched water and atmospheric teleconnection was not highlighted. Nevertheless, it is important to note that despite a strong (positive) similarity with all teleconnection indexes, a positive AO and NAO are thought to have the opposite effect on the water export from the Laptev Sea than a positive AD [*Thibodeau et al.*, 2014], so the interpretation of those data is not straightforward and require a holistic approach in order to understand the interconnected role of the different atmospheric indexes.

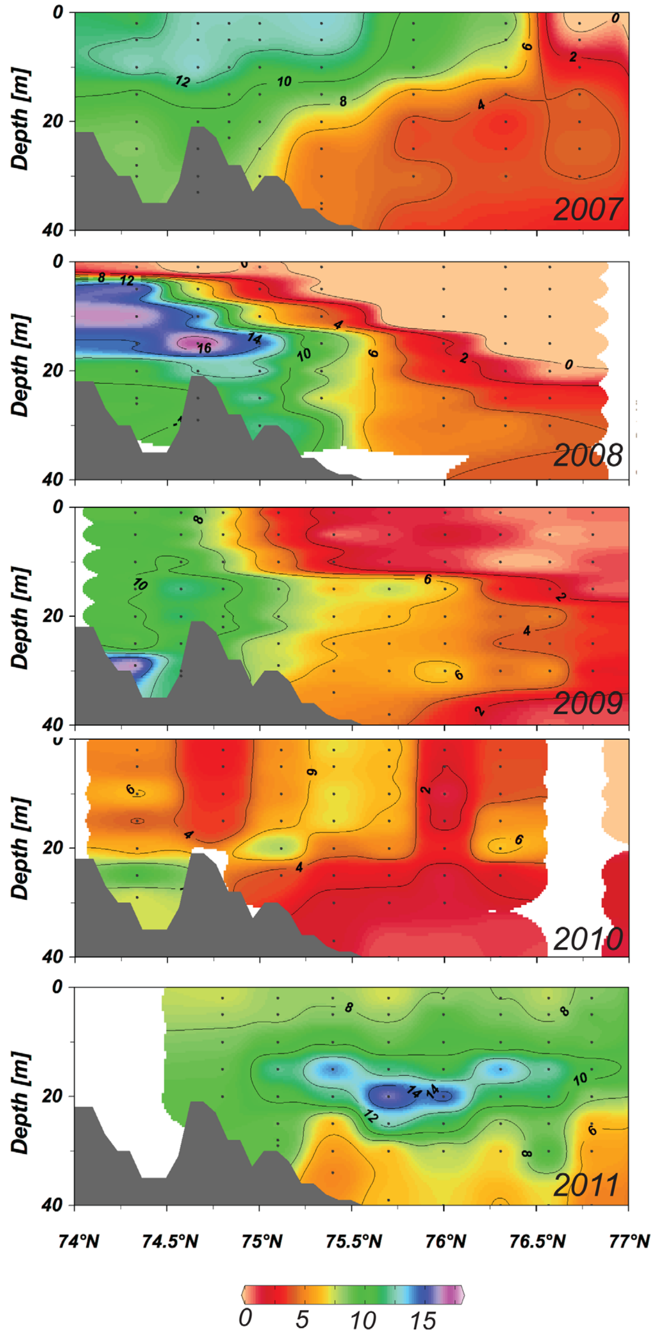

Figure 3. Brine content (in percentage) along 126°E for years 2007–2011. Note that the brine content is the negative fraction of sea-ice meltwater calculated from the water mass analysis (for further explanation see text).

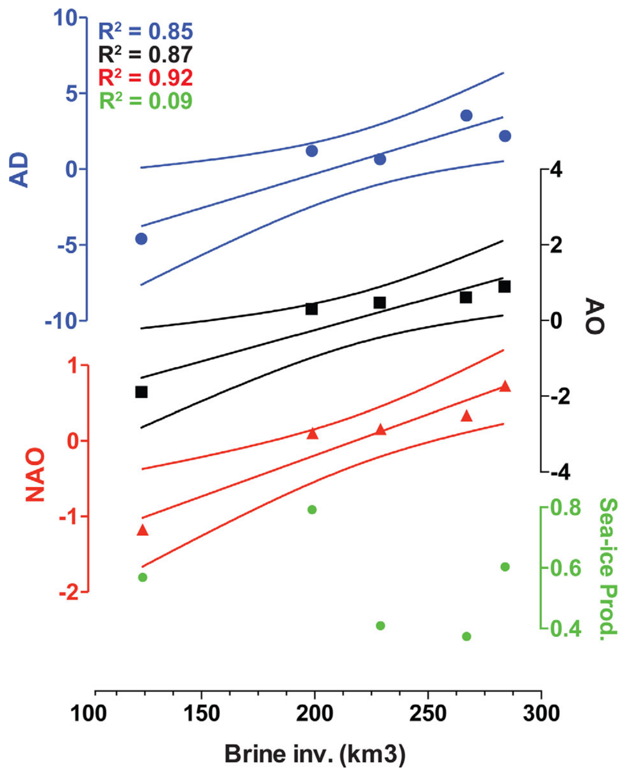

Figure 4. Scatter plot of Winter-Spring Arctic Dipole (AD;DJFMAM) [National Oceanic and Atmospheric Administration, 2015a], Arctic Oscillation (AO; JFMA) [National Oceanic and Atmospheric Administration 2015b], and North Atlantic oscillation (NAO; JFMA) [National Oceanic and Atmospheric Administration, 2015c] in respect to central Laptev Sea brine inventory. Also, the averaged sea-ice production (km^3 d^{-1}) is plotted in green [*Preusser et al.*, 2014]. Statistical elements (linear fit and 95% confidence envelope) are present only to give the reader a quantitative measure of the relationship and should be considered with cautious because of the small data set. Note that the R^2 drops to ~0.7 when adding December and May to the AO and NAO indexes, which suggest that the forcing is more active (or efficient) during JFMA, after the formation of fast-ice.

Table 3. Climate States (Originally Defined by *Watanabe et al.* [2006]) Formed by the Combination of the Winter Arctic Oscillation (AO) and Arctic Dipole (AD) Indexes

Climate State	+DA	−DA
+AO	1	2
−AO	3	4

4.3. Climate State Influence on Brine Inventory

In order to unravel the link between the brine inventory and the different atmospheric teleconnections, we used the four winter climate states originally described by *Watanabe et al.* [2006] and used by *Wang et al.* [2009]. Those four climate states were defined as the four potential combinations of AO (+/−) and AD (+/−) (Table 3). Interestingly, the years characterized by climate state 1 were marked by the highest estimate of brine over the central Laptev Sea shelf (2007, 2008, 2011; Table 4). Moreover, year 2010, which was marked by strong negative AD and AO, had noticeably lower brine amount than the other years.

In state 1 (+AD, +AO), there is a low-pressure anomaly centered on the Laptev Sea while the Canadian Archipelago is characterized by relatively high pressure. The situation is reversed during climate state 4 (−AD, −AO) with a high-pressure anomaly over the Laptev Sea [*Watanabe et al.*, 2006]. Winter climate state 1 is characterized by a pressure anomaly pattern that resembles the atmospheric conditions that have been suggested to cause "onshore" river water export during summer while the high-pressure anomaly over the Laptev Sea in climate state 4 is similar that what have been defined as an "offshore" atmospheric pattern [*Dmitrenko et al.*, 2005; *Bauch et al.*, 2009b]. During onshore years, the winds force the Lena discharge to the eastern part of the Laptev Sea, toward the East Siberian Sea. During offshore years, the river plume is transported northward by the winds, enhancing the export of river water during those years. Offshore summer years are often characterized by a high amount of river water in the central part of the Laptev Sea shelf [*Bauch et al.*, 2009b]. However, years characterized by winter climate state 1 have a high summer brine inventory, especially located in the central part of the Laptev Sea shelf, while year 2010 (climate state 4) has the lowest amount of brine in our data set. Since brines are produced during winter when sea-ice cover is maximal and are mostly found at or below intermediate depth, it is not surprising that under similar atmospheric forcing they may display a different behavior than river water that is mostly discharged at the surface in early summer.

Table 4. Winter-Spring Climate States Based on the Respective Arctic Dipole (AD, DJFMAM) and Arctic Oscillation (AO, JFMA) Indexes Along the Brine Inventory for the Central Part of the Laptev Sea (in km^3)

Year	AD	AO	Climate State	Brine Inventory
2007	3.545	0.613	1	267
2008	0.665	0.472	1	229
2009	1.215	0.306	1	199
2010	−4.585	−1.890	4	124
2011	2.185	0.898	1	284

The low brine content in 2010 might be explained by the observed intensification

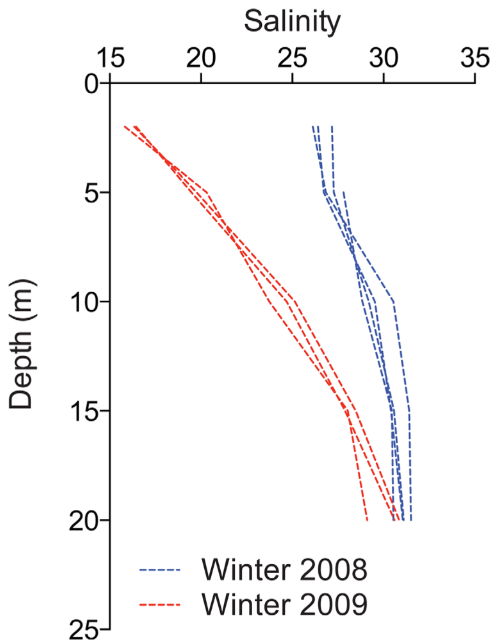

Figure 5. Salinity profiles measured during winters 2008 and 2009 at approximately the same position (~128.4°E/74°N) on the southern limit of the Laptev Sea shelf central zone.

of bottom water advection within the central Laptev Sea shelf in Winter 2010 [*Janout et al.*, 2013]. This event was suggested to be consequent of strong offshore-directed winds and ice drift, which is coherent with climate state 4. The increase of offshore ice drift and surface current was compensated by an intensification of the advection of bottom water. The strong surface and intermediate offshore current might have contributed to flush the brines out of the Laptev Sea shelf in 2010 since most of the brine-enriched water is located between 0 and 35 m depth (Figure 3).

Strong stratification was suggested as a key factor in generating the intense advection of bottom water over the Laptev Sea shelf [*Janout et al.*, 2013]. While winter field data for the low brine event in 2010 are not available, we observed a stronger stratification in winter 2009 compared to 2008 (Figure 5), which is consistent with an enhanced bottom water advection flushing the brine offshore in 2009 and could explain the lower amount of brine in 2009 compared to 2008. The data also indicate that more brine was present in the water column during winter 2007/2008 than in winter 2008/2009 [*Bauch et al.*, 2012], which suggest

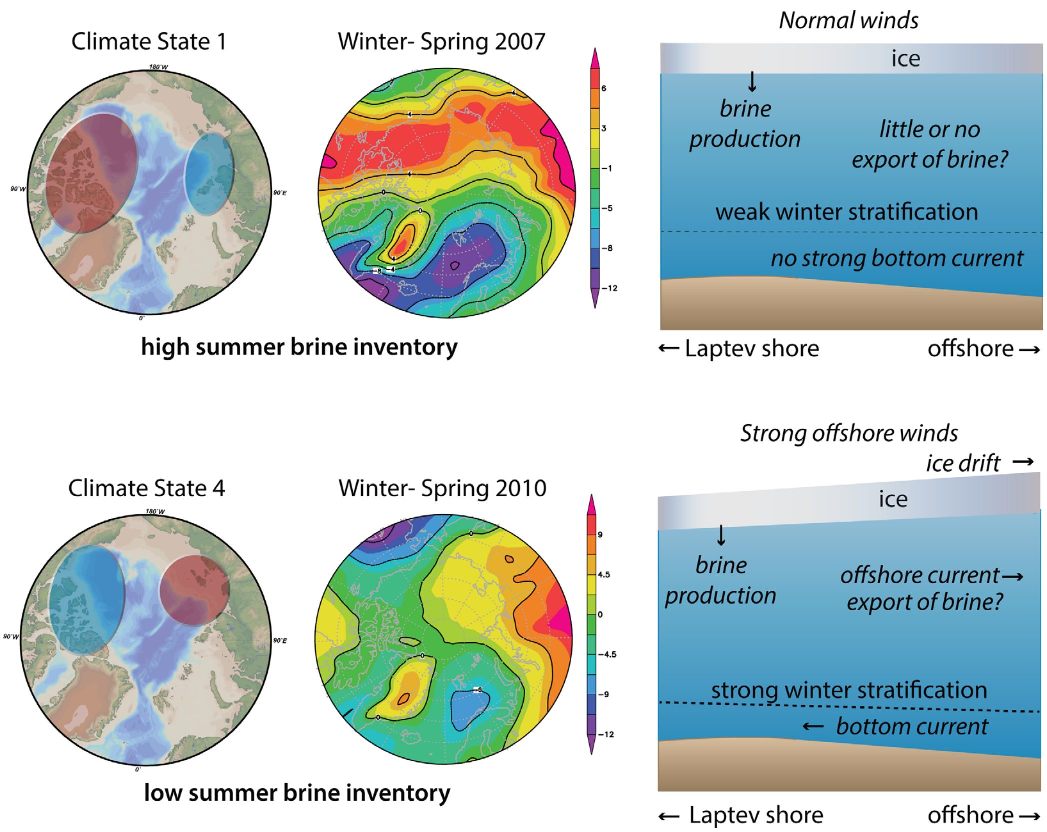

Figure 6. Sketch of the theoretical pressure anomaly for extreme modeled climate states 1 and 4 (respectively, double positive and double negative AO and AD) along with the Sea Level pressure anomaly for winter-spring 2007 and 2010 (representative of climate states 1 and 4 in our data set) and a sketch that illustrates our hypothesis to explain the variability in summer brine inventory between the different climate states.

that the factors controlling summer brine inventories are probably already active at the time of the winter sampling (April), which is coherent with the good fit between the brine inventory and AO indexes between January and April. Consequently, we hypothesize that the 2010 minima in brine inventory was caused by an enhanced export driven by the combined effect of offshore winds and a highly stratified Laptev Sea water column (Figure 6).

5. Concluding Remarks

Our study highlights for the first time the potential link between the temporal evolution of brine inventory over Arctic shelves and large-scale climatic and atmospheric parameters. Surprisingly, we found no relation between the remote sensing-derived sea-ice production and the summer brine inventory. This calls for caution when trying to link directly sea-ice production and shelf contribution (export of brine-enriched waters) to the halocline, because it seems that other parameters might influence the fate of brine over the Arctic shelves, especially during year characterized by extreme negative AO and AD conditions as in 2010. Although warming of the Arctic, and its impact on winter sea-ice production, will certainly impact the brine budget, interannual brine inventory variation seems to be closely related to climatic and atmospheric teleconnections during years 2007–2011. Our results imply that monitoring and predicting the intensity of Arctic teleconnections might provide insight into the future stability of the Arctic halocline and ultimately of the sea-ice cover. Our conclusions stress the need for the use of integrative approaches in order to better understand the complex interaction between the atmosphere, hydrosphere, and cryosphere within the warming Arctic environment.

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